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Art. X.—*Sunspots and Australian Rainfall.**

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In order to guard against any false assumptions with regard to the character of the rainfall response to solar activity of our variously-placed rainfall stations, it was thought advisable to begin this rainfall investigation by a kind of general survey, in which each station is treated individually.

The method followed was to divide the sunspot cycle into three parts, equal in case of a twelve-year period. The first and second are all of four years each; the third usually of three years. The first begins with the year showing by its sunspot number that the rate of rise characteristic of the rising phase of sunspot activity has been attained; the second is the period of the decline; the third is the three or four years covered by the minimum sunspottedness. The rising phase in every case includes the year of maximum sunspottedness.

Now we have many stations scattered over the continent with records covering several sunspot cycles, and we may separate their records in accordance with the treatment of the sunspot cycles. Thus a station with, say, seventy years' record, will cover six complete sunspot cycles, giving twenty-four years under conditions of rising solar activity, twenty-four years for the declining phase, and, say, twenty-two for the minimum periods. Such lengths of record are usually considered sufficient to give a good indication of the average rainfall at most Australian stations.

In the following table practically all the stations with reasonably long records are used. The stations are grouped as conveniently as possible with regard to climatic districts, and their individual average rainfalls for the three phases of the sunspot cycle are given. In addition to these are given the probabilities that the rains during the given phase will be above or below normal. These are simply the result of a count of the plus and minus rainfall departures from the mean for all years. It was not considered in general advisable to take out district means, as even in any one district it could not be said that all stations were under the same climatic control. For example, in Northern Victoria, stations such as Stuart Mill and Swan Hill would not maintain the same rainfall relation from year to year, the former—a hill station—getting much of its rain with the north-westerly and westerly winds of southern disturbances, the latter being almost entirely dependent for its rains upon disturbances of tropical origin. Similar considerations make it obvious that coastal and inland

*Editor's Note.—Publication of this paper has unavoidably been postponed from Part I. of this volume.

stations might be expected to respond differently to solar influences, and, therefore, should not be grouped together.

In general, the rainfalls used are the annual totals, but a partial exception has been made of the south-eastern wheat areas, where the winter rainfall is of paramount importance. The stations for which only the rainfalls of the winter half of the year, May to October inclusive, are shown, are Deniliquin, Wentworth, Adelaide, and a group of ten Northern Victorian stations—Swan Hill, Echuca, Yarrawonga, Warrack-nabeal, Charlton, Bendigo, Shepparton, Dookie, Horsham, and St. Arnaud. For the last, records are available as far back as 1857, though, in the earlier years, not for the whole ten. The numbers of years' record are also given, so that some idea can be formed of the value of the contribution from each stations;—

TABLE I.

Station	No. of years of record	Rainfall average during phases of Sunspot Cycle			Probabilities of rain above normal.		
		Rising 4 years	Decl'ing 4 years	Min'um 3 or 4 y'rs	Rising	Decl.	Min
SOUTH-EASTERN WHEAT AREAS (Winter Rains).							
Northern Victoria (Mean of 10 stations.)	66	1223	1138	963	50	50	17
Deniliquin	64	1034	918	832	50	38	28
Wentworth	55	806	658	582	50	40	33
Adelaide	84	1506	1504	1322	50	48	28
CAPE YORK PENINSULA AND GULF OF CARPENTARIA.							
Mein	35	4865	4761	4629	50	58	45
Georgetown	51	3183	3616	3022	38	60	40
Normantown	51	3936	4065	3755	44	50	47
Burketown	36	3038	2946	2418	33	54	36
EASTERN INTERIOR OF CONTINENT.							
Cloncurry (Q)	39	2309	1965	1594	58	50	9
Springsure (Q)	56	2859	2657	2336	55	50	25
Aramac (Q)	43	2001	1857	1763	50	50	45
Barcaldine (Q)	36	2346	2057	1841	67	31	36
Blackall (Q)	43	2481	2108	1928	63	38	9
Charleville (Q)	45	2256	1984	1791	53	39	25
Tambo (Q)	42	2327	2360	1948	57	40	31
Bourke (N.S.W.)	50	1490	1433	1210	50	53	27
Brewarrina (N.S.W.)	48	1550	1707	1233	50	60	25
Dubbo (N.S.W.)	50	2124	2316	2135	47	56	40
Wilcannia (N.S.W.)	44	1051	962	991	50	44	42
PACIFIC COAST.							
Cardwell	52	8768	8226	8636	53	45	67
Cooktown	49	7186	7407	6836	31	50	33
Townsville	52	5063	4876	4418	53	50	40
Mackay	52	7326	6526	6822	53	40	33
Rockhampton	53	3980	3892	3972	44	40	53
Maryborough	53	4758	4761	4359	39	55	33
Gympie	53	4559	4617	4383	44	50	40
Brisbane	71	4506	4727	4391	33	50	43
Sydney	83	4749	4616	5133	36	27	50

Station	No. of years of record	Rainfall average during phases of Sunspot Cycle: Rising 4 years	Decl'ing 4 years	Min'um 3 or 4 y'rs	Probabilities of rain above normal: Rising	Decl.	Min.
Pacific Slope and Tablelands.							
Charters Towers	41	2821	2210	2410	57	50	47
Clermont	47	2943	2686	2679	50	56	31
Taroom	47	2896	2613	2555	54	42	47
Dalby	53	2695	2509	2540	67	45	27
Banana	52	2898	2752	2524	65	55	40
Goondiwindi	44	2615	2542	2429	56	50	42
Warwick	58	2882	2709	2805	55	30	44
Bathurst (N.S.W.)	64	2479	2424	2213	48	46	41
South Australia—Upper North.							
Outalpa	55	932	988	857	50	45	40
Port Augusta	63	995	1043	834	52	42	33
South Australia—Western Interior.							
Yardea	46	1018	1098	1092	38	44	50
Territory and Central Australia.							
Katherine	50	3621	4135	3858	38	58	47
Daly Waters	50	2305	3071	2511	19	63	38
Powell's Ck.	49	1668	2102	1744	25	67	33
Tennant's Ck.	49	1463	1587	1405	38	67	53
Alice Springs	49	973	1323	1043	31	56	20
Charlotte Waters	49	455	631	602	38	50	47
William Ck.	49	485	598	556	44	56	47
N. and W. Coastal.							
Darwin	53	6296	6488	5689	56	45	20
Wyndham	37	2741	2643	2605	58	43	55
Derby	37	2685	2800	2471	42	43	55
Cossack	41	1160	1114	1188	37	44	27
Onslow	37	904	898	881	50	36	36
Carnarvon	40	1023	968	817	69	50	27
Geraldton	45	2018	1789	1815	50	38	36
Perth	47	3489	3412	3249	53	38	47
Bunbury	46	3580	3766	3569	44	50	43
West Australia (Slightly Inland).							
Mt. Florence	36	1628	1497	1395	58	54	18
Northampton	41	2138	2010	1944	64	50	36
Walebing	39	2242	1916	1772	75	38	36
York	46	1943	1736	1563	63	44	36
Southern.							
Albany	46	3778	3712	3519	63	38	43
Eyre	38	1145	1121	1184	42	47	55
Eucla	47	1000	969	1007	50	44	60
L. Hamilton	46	1717	1658	1698	63	38	50
Pt. Lincoln	57	2080	1942	1860	70	50	41
Melbourne	80	2676	2694	2463	50	48	35
Hobart	82	2445	2397	2247	46	48	28

Inspection of the table shows that it is in the inland portion of the eastern half of the continent, and especially in the south-east, that the rainfall shows the most direct response to solar activity. Taking, for example, the sixty-six years' record for the ten Northern Victorian stations, we find that for the six four-year periods of rising sunspot activity the mean winter rainfall for the group is 12.2 inches; for the six four-year periods of declining sunspot activity, 11.4 inches; and for the eighteen years of minimum sunspot activity, 9.6 inches. These are striking results. That they are not influenced unduly by the occurrence of three of our worst drought years during minimum sunspot periods, may be seen by counting for these the number of years with rainfalls above the general average. These were only three out of a total of eighteen. Hence, while the probability of a good year occurring is fifty per cent. for the rising and early declining phases, it is only seventeen per cent. for the minimum phase of sun-spottedness. Similar results are given by the individual stations, Deniliquin and Wentworth. With Adelaide, the only thing definite is the dryness of the minimum period.

A good example of the usefulness of the table of probabilities of rains above normal is afforded by Cossack, where the highest average rainfall was that for the minimum phase of sunspot activity, and yet the actual probability of a good season is least during these periods. The anomaly is due to an excessive rainfall, over forty inches, during one of the minimum sunspot years. Alice Springs provides a somewhat similar case. Such anomalies are, however, comparatively rare.

It is fairly evident from this table (1) that the rainfall of the whole of the continent is affected in some way by the solar activity; (2) that it is not affected everywhere in the same way. This is, however, rendered clear by mapping the percentage rainfall departures from normal for all stations during the three chief phases of solar activity. This involves three maps, which were constructed as follow;—

Map I. deals with the sunspot minimum periods, and shows the rainfall in percentage departures from the general mean or normal.

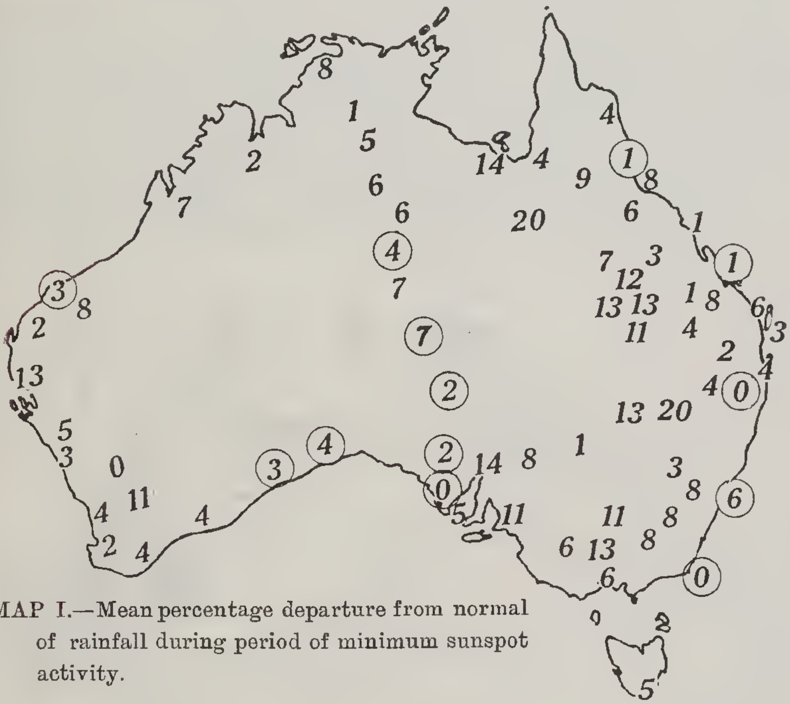
Map II. shows, in the same way, the departures from normal for the rising phase of sunspot activity.

Map III. shows the departures from normal during the declining phase of sunspot activity.

The map results differ widely from one another, and may be described as follows;—

Map I.—The rainfall during the minimum periods of sunspot activity is depressed over the whole eastern interior of the continent by amounts generally ranging between ten and twenty per cent., and to only a slightly less extent over the western interior and Northern Territory. Over east coast areas and those central areas between the Bight, and, say, Barrow's Creek, it is practically unaffected.

Map II. (rising phase) shows a very great rainfall rebound over the eastern interior and West Australia, of from ten to over thirty per cent., thus carrying it well above normal for the rising period of sunspot activity, but little change on the east coast except that there was an eight per cent. fall at Sydney. There was a further decline over Central Australia and the Territory.



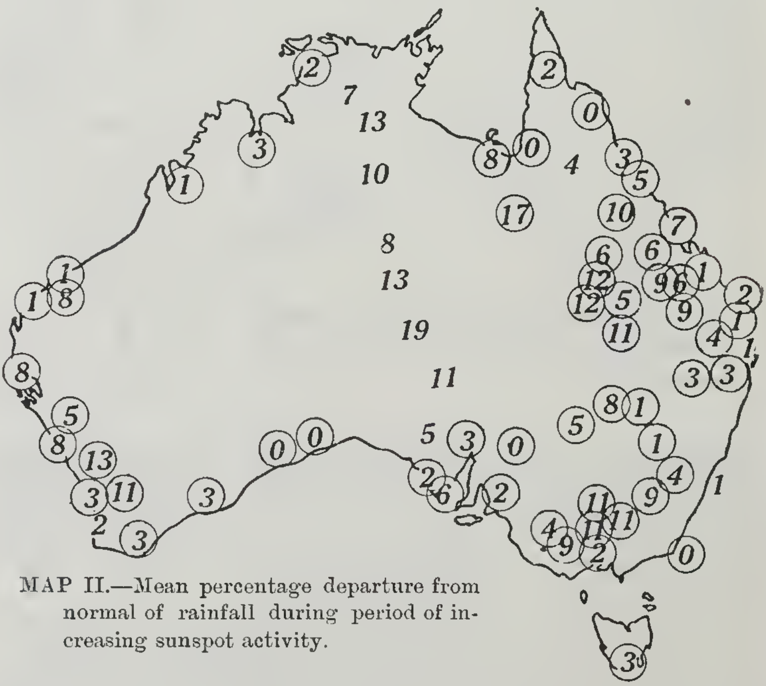
MAP I.—Mean percentage departure from normal of rainfall during period of minimum sunspot activity.

Map III. (declining phase) shows over the eastern interior and in Western Australia a marked decline, bringing the rainfall back to about normal, but a great rise in the rainfall over the Territory and right across the continent to the head of Spencer Gulf, making this distinctly the wettest period. This is probably a feature of great significance.

In the light of our knowledge of Australian meteorology, some tentative explanation of these effects may be offered.

Map I.—It seems probable that the failure of the rain over the eastern interior of the continent during the sunspot minima is due to diminished energy or frequency of the air flows from the tropics, coming by way of New Guinea, Cape York Peninsula, and the Gulf of Carpentaria. The similar rain failure over the western portion of West Australia also points to a weakening of tropical influences, but shown in another poleward-flowing current or equatorial offshoot. This naturally affects the rain production of the disturbances reaching Victoria from that direction by way of southern waters. The maintenance of the rainfall over the east coast may be due to the greater frequency of cyclonic developments off the east coast. Certainly these occur with marked frequency in some years when cold nights and anticyclonic conditions generally are the prevailing experience over the interiors of Queensland and New South Wales.

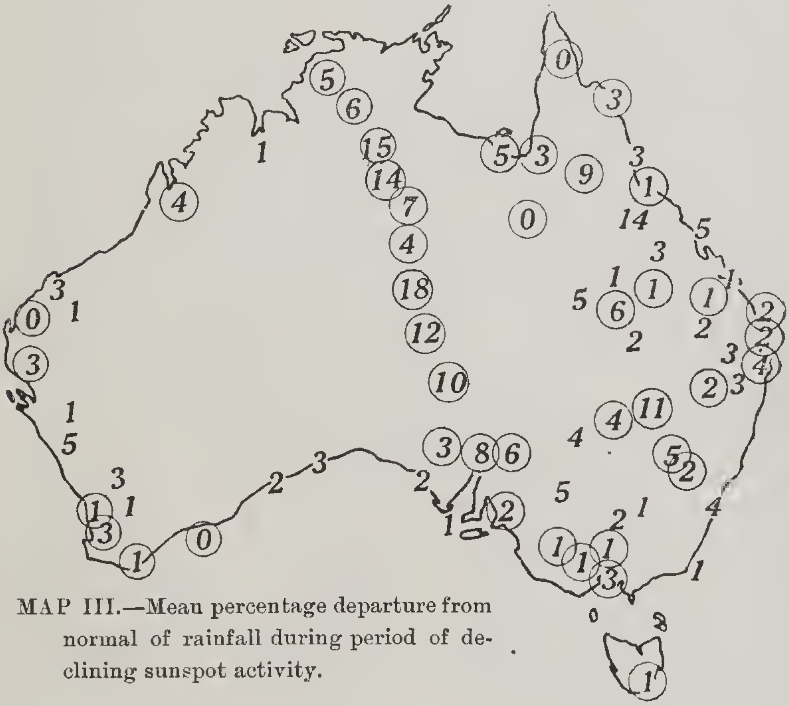
Map II.—The remarkable rise to a maximum of the rainfalls over the eastern and south-eastern interior of the continent and in the west during the rising phase of the sunspot cycle, points to recovery of tropical energies, and may be partly due to increased convectional energy over the land areas under the brighter sunshine during the dry minimum sunspot period, but, if so, it is curious that the rainfall continues to decline over the central areas and the Territory. The remarkable



MAP II.—Mean percentage departure from normal of rainfall during period of increasing sunspot activity.

falling-off in the Sydney rainfall points to a lessening in frequency of east-coast cyclones, or such a change in the general air circulation as to increase the shielding effect of the Blue Mountains.

Map III.—For this, the declining phase, the rainfall becomes practically normal over the eastern interior and Western Australia, but makes a most remarkable rise over the Territory, and thence as far south as Spencer Gulf. For the latter, explanation is difficult. It would seem, however, to be a delayed effect, and may be partly due to the necessity for waiting until water accumulations have become fairly common, as well as some recovery in the growth of vegetation. At all events, this would, to some extent, meet the case of the lessened decline



MAP III.—Mean percentage departure from normal of rainfall during period of declining sunspot activity.

in rainfall during the minimum sunspot period over this area, as compared with that over the rest of the interior. It is probable, however, that the chief cause must be sought in the modifications of the general atmospheric circulation resulting from the variation in solar activity. For example, if, during the rising phase, the eastern and western interiors of the continent are the loci of two separate southward outflows from the equatorial belt, then the area between them, Central Australia and the Territory, may be in the path of return currents, and its dryness explained. The further fall in the Sydney rainfall suggests an increasing west-east drift of the air over the Southern Seas and southern portions of the continent.

Remarks on the Graphs.

Below (Fig. 1) are given graphical representations of the last seven cycles of sunspot frequency and of the rainfalls of various typical inland stations with long rainfall records. The rainfall in each case has been smoothed, the value plotted for any year being the mean for the three years centred about that year. This has the effect of eliminating irregularities due to a suspected three-year period. Of these, Bendigo, which, with the aid of Heathcote during the very early years, goes back as far as 1857, is typical of Northern Victoria. This shows, probably, the closest agreement with the sunspot curve. The annual and the winter (May-October) rains are shown separately. For the latter, I have computed the correlation coefficient, first for the rainfall curve smoothed, next for the curve unsmoothed. The smoothed curve gives the very high correlation coefficient of +0·63 (nearly), with a probable error of only ±0·050. This is a high coefficient, and, as the probable error is small, less than one-twelfth of the correlation coefficient, it can scarcely be doubted that the variation in solar activity is a dominant factor in the winter rainfall of Bendigo. For the unsmoothed curve, or the actual rainfalls, the correlation coefficient is +0·46. The fact of there being such a difference may be taken as pointing to the existence of a three-year period in connection with the rainfall.

Testing Cloncurry and Springsure rainfalls in the same way, we get correlation coefficients of +0·34 and +0·35 respectively, with probable errors of ±0·099 and ±0·079. These, though reasonably good, are not such indications of solar influence as the Bendigo rainfalls, for which the shorter records and greater rainfall variability are probably partly to blame.

Very interesting results are obtained from the central areas, extending from the Bight to the Upper Territory. As the maps show, the maximum rainfalls here do not occur with, but some years after, the maximum sunspottedness, and a similar lag is shown with minimum rainfalls and sunspottedness.

As three years appeared to be about the amount, I correlated the rainfalls of Daly Waters with the sunspot totals of three years previously. The correlation coefficient proved to be +0·61 with probable error ±0·062. This is nearly as striking a result as that for Bendigo. The record is a long one—fifty-one years. Assuming the lag to be four years gave better results still, a correlation coefficient of +0·64±0·057.

Alice Springs rainfalls, treated in the same way, gave a lower correlation coefficient, +0·36, probable error, ±0·088. The lag is not quite so apparent here, and there is some confusion of the factors governing rainfall. Adelaide has the longest record of all, eighty-five years. It is almost in the same belt

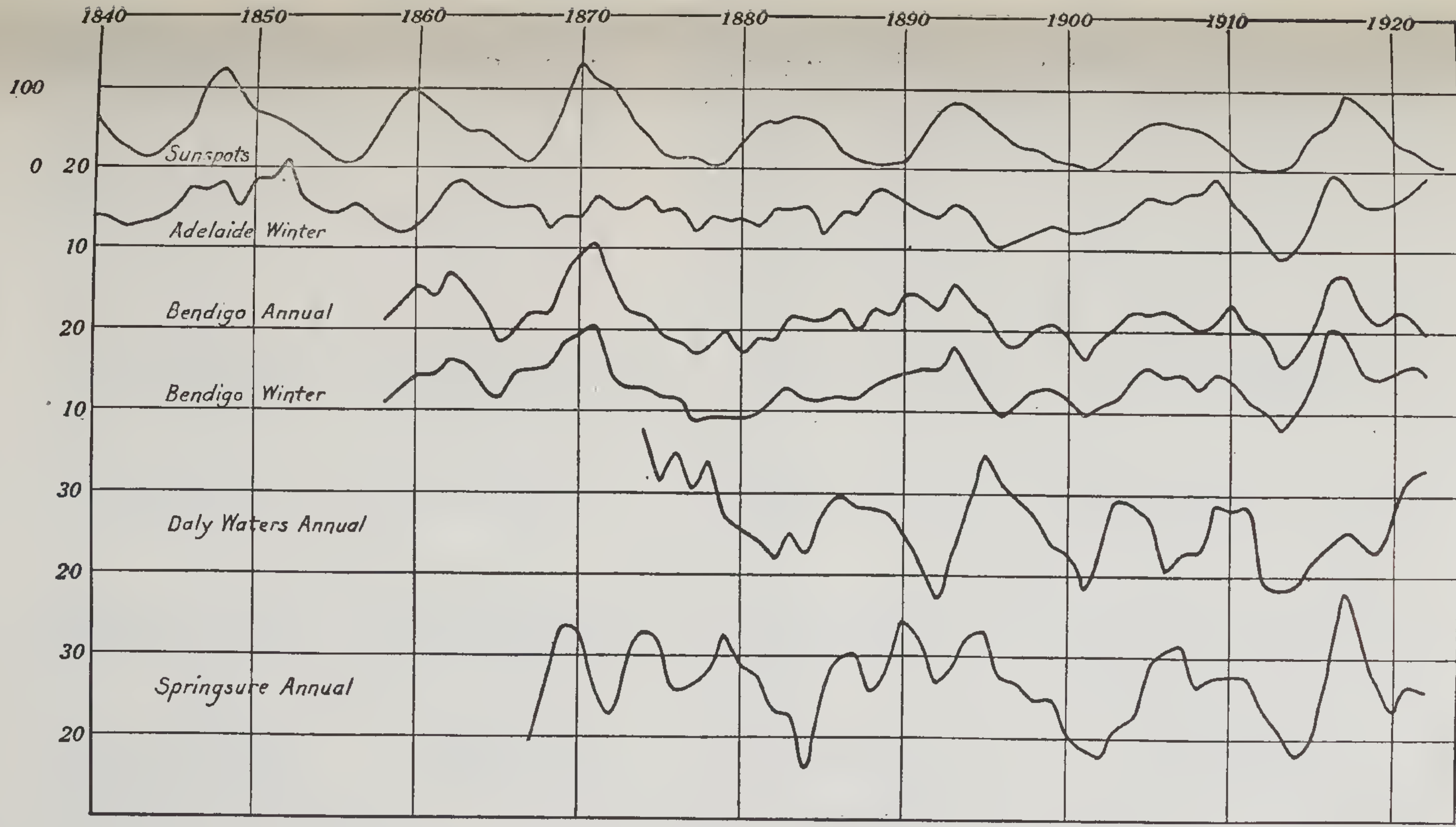


Fig. 1—Correlation between Rainfall and Sunspots: First Curve Wölfer Smoothed Sunspot Numbers; Remainder, Three-Yearly smoothed Values of Annual or Winter Rain. One Vertical Division equals 100 in Spot Numbers or 10 Inches in Rainfall. Actual Rainfall at each Station is Indicated by Figures on Left of Diagram.

as the stations of Central Australia, but may be regarded also as a coastal station, and its rainfall relation to the sunspot curve is thus rendered more complex. Its smoothed winter rainfall curve has a coefficient of +0·32 with probable error of ±0·067 when correlated directly with the sunspot curve, and +0·21 when compared with the sunspot figures of three years earlier. Inspection of the curves suggests a rainfall lag for the maximum rainfall, but not for the minimum rainfall. I accordingly tried correlating this rainfall with the sunspot curve modified systematically, so as to throw the maximum sunspottedness about two years later. This gave a coefficient of +0·37, probable error ±0·061. The modification was accomplished by joining with a straight line the point for the third minimum year with a point midway between the points for the fifth and sixth years following. This point was substituted for that of the fifth year. Assuming a three-year lag, Powell's Creek gave +0·44 ±0·078, and Tennant's Creek +0·23 ±0·091. These correlations suggest that Bendigo and Daly Waters respond most completely to sunspot activities, the former immediately, and the latter with a lag of four years, and it seems probable that other stations follow one or both of these.

It may be remarked that the use for correlation purposes of the winter six months' rainfall of the inland stations of the south-east quarter of the continent is justified economically, but, from inspection of the curves, it is obvious that it matters little whether the winter or annual rainfall is taken. The winter rainfall is dominant for this area.

Average annual rainfall variations with Sunspot Cycle.

Very interesting results are obtained by grouping the rainfalls of the more important long-record stations, in accordance with the sunspot periods, and obtaining the mean rainfall for each year of the sunspot cycle. As Bendigo may be taken as typical of all Northern Victoria, and has the longest rain record of any such station, I began with that.

The following table and figure 2 show the arrangement and mean results. As we have practically six complete cycles, we get, except in the case of the twelfth year, the records of six years to determine the mean rainfall for each year of the sunspot cycle. From the first to the fourth year, when the sunspottedness is usually at its maximum, the rainfall is rising to its maximum. Then the rainfall begins to decline, not regularly, but so as to reveal drought tendencies every third year, or in the sixth, ninth, and twelfth years of the sunspot cycle, the last being much the worst. These drought years, with successive rain totals of 19.4, 17.0, and 14.0 inches, are so emphatically below the average rainfall, 21.4 inches, that

TABLE II.

RAINFALL IN RELATION TO SUNSPOT CYCLES.

Cycle Com'ncing	1857		1868		1880		1891		1903		1915		Mean All Cycles	
Order in Cycles	A	B	A	B	A	B	A	B	A	B	A	B	A	B
							BENDIGO, ANNUAL RAINFALL.							
1	(2090)	2	1734	4	2237	3	1979	7	2810	8	1963	5	2136	4.8
2	(2450)	6	2154	3	1290	1	2685	8	1983	3	2880	8	2240	4.8
3	2180	5	3837	8	2162	5	2109	3	1912	4	3011	7	2535	5.3
4	2530	5	2712	5	2178	6	2881	10	2746	8	2195	6	2540	6.7
5	2820	10	2625	6	2180	5	2091	5	2102	5	1625	4	2240	5.8
6	1850	4	2054	5	2016	5	1625	3	1592	3	2511	6	1941	4.3
7	3392	9	1958	3	2139	5	1867	3	2392	6	2633	8	2397	5.7
8	2303	8	2482	7	2625	7	1967	2	2295	7	1384	1	2176	5.3
9	1085	1	1400	3	1238	1	2175	5	2321	6	1977	4	1699	3.3
10	2141	7	1696	4	2829	7	2083	6	1587	4			(2096)	(5.6)
11	2666	5	2044	3	2485	4	1534	4	2009	3			(2148)	(3.8)
12			1637	4			1350	2	1211	2			(1399)	(2.7)
Means	2280	5.6	2194	4.75	2125	4.5	2029	4.8	2080	4.9		3.8		
							BENDIGO, WINTER RAINFALL.							
1	835	1	981	2	901	0	1101	3	1592	4	1645	5	1176	2.5
2	1029	2	1442	2	811	0	1859	5	1307	2	2145	5	1432	2.7
3	1381	4	3002	6	1187	3	1598	2	1381	3	2315	5	1811	3.8
4	1313	2	1402	1	1569	4	1934	6	1973	5	1400	3	1597	3.5
5	1557	4	1729	3	1121	2	875	1	942	1	819	1	1174	2.0
6	1423	3	1195	2	1068	1	708	0	1212	2	2062	5	1278	2.2
7	1931	6	929	0	1222	3	1277	2	1743	3	1693	5	1466	3.2
8	1273	4	1683	4	1296	3	1413	1	1481	4	1027	1	1362	2.8
9	782	1	917	2	923	0	1169	1	977	2	1770	4	1090	1.7
10	1390	4	875	2	1683	4	1263	3	1080	2			(1258)	(3.0)
11	2149	4	827	0	1652	3	1072	3	1046	1			(1349)	(2.2)
12			1013	2			591	0	321	0			(642)	(0.7)
Means	1369	3.2	1333	2.2	1221	2.1	1238	2.25	1255	2.4	1653			
							DALY WATERS, ANNUAL RAINFALL.							
1	—		—		2244		1218		2187		1886		1889	
2	—		—		1897		1815		4595		2557		2716	
3	—		—		3117		2087		1906		2545		2418	
4	—		—		1581		2961		1687		2598		2207	
5	—		—		2825		2538		2621		2137		2780	
6	—		4391		2406		3921		2496		2204		3084	
7	—		3272		2927		1913		1753		3878		2749	
8	—		3603		3584		2977		4325		3575		3613	
9	—		2552		2023		3288		2444		2484		2558	
10	—		4248		2905		899		1811				2216	
11	—		2358		3289		2658		1648				2488	
12			3509				1966		2074				2516	
							DENILIQUIN, ANNUAL RAINFALL.							
1	—		1269		1459		2147		1605		1315		1559	
2	—		1328		1362		1691		1452		1933		1553	
3	1327		2405		1507		1518		1369		2508		1772	
4	1883		2077		1482		2408		2732		2033		2102	
5	1510		1739		1090		1259		1116		1491		1367	
6	1210		2254		1670		1188		1083		1653		1510	
7	2538		1827		1394		1282		1521		1745		1718	
8	1302		2414		2197		1391		1785		811		1650	
9	871		1366		884		1390		1507		1641		1277	
10	1489		1265		2607		1348		1950				1731	
11	2058		2810		1805		1105		1254				1806	
12			1428				1113		554				1032	

NOTE.—The figures in columns "A" represent rainfall in points (1 point = .01 in.); those in columns "B", the number of months with rainfall above normal.

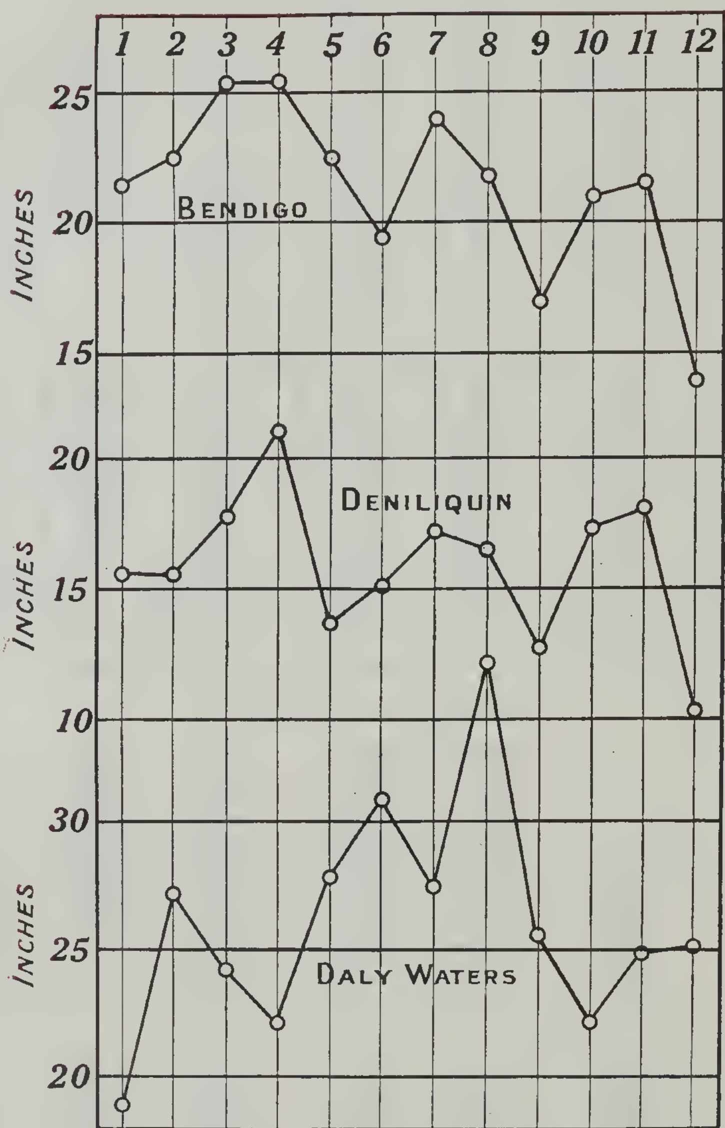


Fig. 2.—Rainfall Variation during Sunspot cycle.

one can hardly help concluding that we have here made evident the operation of a three-year cycle. As, however, it is not apparent during the rising phase, it is natural to conclude that the increasing solar activity is such as to cause a sort of forced oscillation, after which terrestrial influences become manifest in a three-year period. To show whether these results really represent the rainfall characteristics of the various years, I counted the number of months in each year with rainfall above normal, and took out the means. These well support the rainfall means, but are a little more emphatic in favour of the fourth year as the wettest. Taking the winter rains only (May-October), very similar results are obtained, but, according to them, the third year is slightly wetter than the fourth, and the fifth year slightly drier than the sixth.

Treating the annual rainfalls from Deniliquin in the same way, we get the fourth year as the wettest, the fifth drier than the sixth, but both below normal, and the ninth and twelfth very dry. Its winter rains closely agree with those of Bendigo. Daly Waters gives equally striking results. Assuming a four-year lag, and placing its fifth year under the first of the sunspot cycle, we get a rainfall variation very much like that of the two preceding stations, but showing the tendency to a three-year period even more strongly—the first, fourth, seventh and tenth all being dry years. Such good agreements with solar activity as these results show might, of course, have been anticipated from the high correlation coefficients obtained between the rainfall and sunspot curves, but they are useful to indicate the probability of a three-year rainfall period as well as the eleven or twelve-year agreement with the solar period.